韓國地形空間情報學會論文集 第4卷 第2號 1996年 12月 pp. 55-61

GIS를 이용한 분기형 관로의 최적설계

Optimal Design of Branched Water Supply System with GIS

김 중 훈* 연 상 호** 김 종 우***

Kim, Joong-Hoon Yeon, Sang-Ho Geem, Zong-Woo

要 旨

본 논문의 목적은 분기형 관로에 대해 선형계획법을 이용하여 최적의 설계를 하는데 있다. 그리고 자료의 획득과 계산결과를 표시하는 측면에서 GIS의 도움을 받아 전체작업을 좀 더 신속하고 용이하게끔 하였다.

개발된 모형은 송수터널이나 정수장같은 수리부속물의 영향도 고려해 주었으며 특히 송수터널같이 관로와는 다른 체계를 갖는 비용을 목적함수에서 고려해줄 수 있었다.

목적함수는 초기건설비측면뿐 아니라 연간유지비측면의 비용까지도 고려해주어 보다 합리적인 결과를 제시해주었으며 계산된 수리결과도 보다 실무적으로 제시되었다. 예를들어 결정변수로 관경대신 관길이를 잡음으로해서 이산적인 형태의 관경을 고려해줄 수 있었다. 그리고 최적 양정고는 물론이고 양수장의 위치와 갯수까지도 구해 낼 수 있었다.

GIS는 수리학적 자료나 비용자료를 자동으로 다루거나 계산된 최적의 결과를 가시화하는데 이용되었다. 특히 실제하는 관로시스템에 적용되었으며 GIS의 도움으로 보다 경제적인 설계를 할 수 있도록 의사결정과정상에 도움이 되었고 이로써 실무에도 훌륭히 적용될 수 있는 모형이라 생각되었다.

ABSTRACT

The objective of this paper is to show an optimal design model for branched water supply system which also can find the optimal location of pumping stations using linear programming. GIS is utilized in this model to better handle the data and the results from the optimization.

The developed model considers hydraulic influences of some appurtenances such as supply tunnels and a filtration plant. The model also considers tunnel construction cost which should be treated differently from pipe construction cost. Different from other models presently available, the model guarantees a nonnegative pressure at every junction node in the system.

The objective fuction includes annual operation cost (electricity rate) in addition to initial construction cost, thus producing a more reasonable decision. The model selects the optimal diameter not in the form of continuous number but in the form of commercial discrete diameter (pipe size) using the pipe lengths as decision variables instead of pipe diameters. The model not only determines the optimal pumping head for each pumping station but also finds the optimal location and number of pumping stations.

GIS is used to handle hydraulic and budgetary data automatically and to visualize the results for the optimal design of the system. The model has been applied to an existing water supply system. The results show that the optimization model with the aid of GIS is helpful in the decision-making process for the design of more economical systems, and can be put into practice successfully.

*고려대 토목환경공학과 교수 **한국지리정보산업협동조합 전무이사

***고려대 토목환경공학과 박사과정

1. Introduction

Pipeline system is needed in order to supply water from source nodes to demand nodes with no loss and safe. There are two types of pipeline system in the aspect of pipe layout. One is looped type and the other is branched type.

Generally, the design procedure of branched type water supply system is as follows. First, discharge in each pipe is assigned from node demands. And diameter of each pipe is computed using discharge, head loss, pipe length, roughness. The number and position of pumping station is determined by expert's experience. But here, the branched water supply system is designed not acording to traditional procedures but to optimal procedure using linear programming and GIS.

2. Optimal design model

The optimal design model for branched system using linear programming is

Objective function :

Minimize

$$Z = \sum_{(i,j)\in I} \sum_{m\in M_{i,j}} c_{i,j,m} X_{i,j,m} + \sum_k CP_k P_k \quad (1)$$

Constraints :

Subject to

$$\sum_{m\in M_{i,j}} X_{i,j,m} = L_{i,j} \qquad (i,j)\in I \qquad (2)$$

$$H_{\min,n} \le H_s + \sum_k XP_k - \sum_{(i,j)\in I_n} \sum_{m\in M_{i,j}} J_{i,j,m} X_{i,j,m} \le H_{\max,n}$$

$$n = 1,\cdots,N \qquad (3)$$

$$XP_k \le XP_{MAX} \qquad (4)$$

$$X_{i,j,m} \ge 0, \quad P_k \ge 0 \qquad (5)$$

Where :

Mi,j = the set of candidate pipe diameters for the pipe connecting nodes i and j

ci,j,m = the cost per unit length of the mth diameter for the link connecting nodes i and j

Xi,j,m = the length of pipe segment of the mth diameter in the pipe reach between nodes i and j.

CPk = the unit cost of pumping power at location k

XPk = the pumping head at location k

XPMAX = the maximum pumping head

Pk = the pumping power at location k

Li,j = the length of the link connecting nodes i and j

Hs = known elevation of water source which is a fixed grade node

Ji,j,m = hydraulic gradient of the pipe of diameter m connecting nodes i and j

Hmin,n = minimum allowable head requirement at delivery point n

Hmax,n = maximum allowable head requirement at delivery point n

I = the set of pipe links that define the network

In = the set of pipes that defines the path to node n (delivery point n)

N = total number of delivery points

Objective function is divided into 2 parts. One is pipeline cost and the other is pumping cost. In eq.(1), first term in right hand side represents pipeline cost which is the product of pipe cost per unit length and pipeline length. Second term represent pumping cost which is the product of pumping cost per unit power and pumping power.

Constraints are divided into 4 types such as total length constraint, head range constraint, pump capacity constraint and none negativity constraint. But continuous constraint in each node is not needed because the discharge in each pipe can be determined before computation of branched system.

Total length constraint is that the total length between adjacent two nodes equals to the sum of lengths of various diameter sized pipes. Head range constraint is that the head at each demand node must be located between minimum allowable head and maximum allowable head. Pump capacity constraint is that computed head can not exceed the maximum head of pump capacity. None negativity constraint is that pipe length and pump power can not be negative

To find the optimal locations of pumping stations, two step method is used. First step of 2 step method is to operate optimization with all pumps in possible locations. After optimization, the pumping heads of some pumps are risen remarkably, but those of others are almost plain. Second step is to operate optimization again with some pumps which have remarkable pumping heights before computation. And then the optimal locations and pumping heads can be obtained.

3. Cost functions

3.1 Classification by expenditure occurrence

For the sake of considering annual operation cost(electricity rate) and initial construction cost together, initial construction cost in the form of single-payment is converted to the cost in the form of uniform annual series. Initial cost is converted to annual type cost in two ways. Two equations are as follows.

$$C_1 = C_I\,Fa + C_o \tag{6}$$

$$C_2 = C_I\,(i + Fd + Fm) + C_o \tag{7}$$

where CI is initial construction cost, Fa is uniform annual series factor(capital-recovery factor), Co is annual operation cost(electric charges), i is annual interest rate, Fd is depreciation rate and Fm isasset maintenance rate.

Eq(6) is called formular substitution method and uniform annual series amount is computed by adding the product of initial cost and capital-recovery factor to electric charges of pure annual cost. And capital recovery factor is

$$Fa = \frac{i\,(1+i)^n}{(1+i)^n - 1} \tag{8}$$

where i is annual interest rate, n is the number of years.

Eq(7) is called simple multiplication method and uniform annual series amount is computed by adding the product of initial cost and interest rate, depreciation rate, asset maintenance rate to pure annual cost.

3.2 Classification by expenditure types

Cost is divided into 4 types of costs which are pipeline construction cost, pump equipment cost, pumping station construction cost, and electric charges. The total cost is

$$W = W_1 + W_2 + W_3 + W_4 \tag{9}$$

where W1 is annual amount of pipeline construction cost, W2 is annual amount of pump equipment cost, W3 is annual amount of pumping station construction cost, and W4 is annual amount of electric charges.

Annual amount of pipeline construction cost is obtained by substituting initial pipeline construction cost to eq.(6) or eq.(7). And initial construction cost is computed by multiplying unit length pipe construction cost and pipeline length. Pipe construction cost per unit length is shown in table 1 and annual interest rate is 10%, durable years of pipe is 35 years, depreciation rate is 2.57%, asset maintenance rate is 0.7%.

Table 1. Pipe Construction cost

Diameter (mm)	Pipe Cost ($/m)	Working Cost ($/m)	Construction Cost ($/m)
700	145	208	353
800	179	255	434
900	200	289	489
1000	241	351	592
1100	261	430	691
1200	308	486	794
1350	365	555	920
1500	425	645	920
1650	503	740	1243
1800	569	909	1478

Annual amount of pump equipment cost is computed by substituting the product of unit power pump equipment cost(625$/kW), maximum pumping power(kW) and pump spare rate(133%) to eq.(6) or eq.(7).

Annual amount of pumping station construction is computed by substituting the product of unit area pumping station construction cost(875$/m2) and pumping station area(m2) to eq.(6) or eq.(7). Pumping station area(m2) is represented as linear function of maximum pumping power(kW). The formular of pumping station area is

$$A = 0.65P + 39.0 \qquad (10)$$

Annual amount of electric charges is computed by multiplying unit hour electric charges and maximum pumping power and 8760hours(= 1 year)

4. Data management using GIS

For the purpose of handling data using GIS, digital map is needed. Digital map is classified into 2 types. One is base map and the other is thematic map.

Base map contains the locations of various objects such as rail road, highway, river, administrative boundary. Here the zone of base map is the capital region of Seoul and the scale is 1 : 250,000.

Thematic map is produced for specific goal. In this research, there are two thematic maps. One is node map and the other is pipeline map. Node map contains not only the coordination of each node but also node names, gound heights and water demands as property data. Pipeline map also contains the length of each arc betweetadjacent nodes.

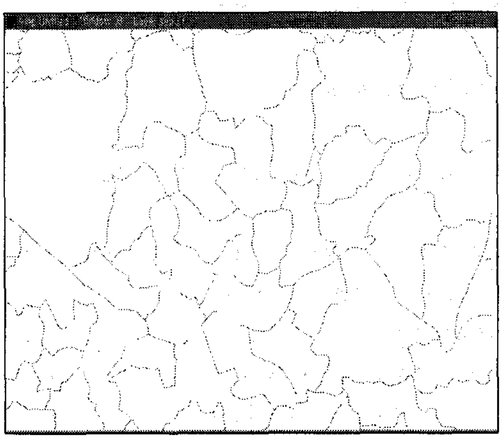

Fig.1 Administrative boundary layer

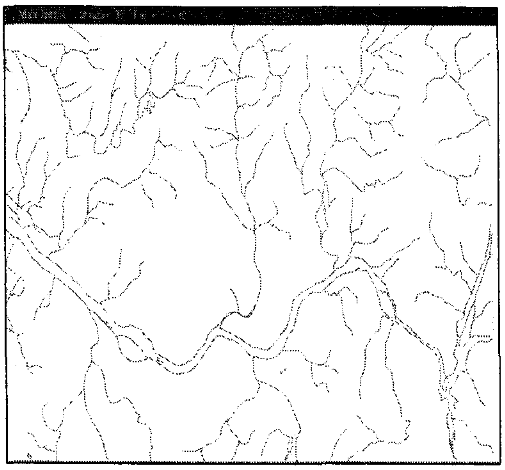

Fig.2 Water boundary layer

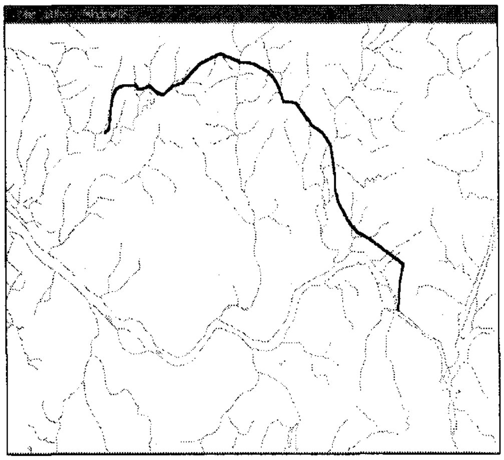

Fig.4 Pipeline layer

Using node data, pipeline data and cost data such as pipe construction cost, pump equipment cost and pumping station construction cost in another data base, the input source code of optimization package is prepared.

Optimization package is operated on DOS and produces the result in the form of ASCII format. In order to read this data, the ASCII formatted result data must be converted to the data-base formatted data. On reading the result data, computed diameters in various colors and computed pump locations are shown on the digital map.

The figure of data flow is as follows. Where GIS software is SPANS Explorer(Version 1.1, 1995), and Optimization package is GAMS(General Algebraic Medeling System, Release 2.25, 1992).

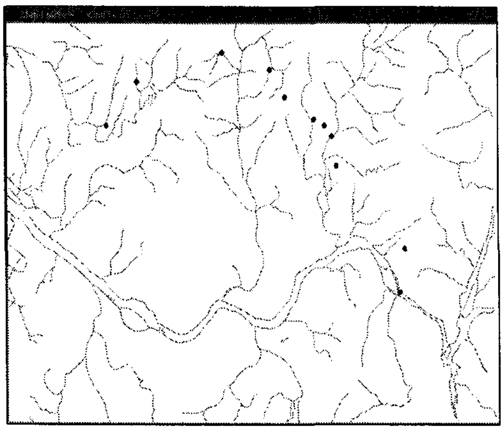

Fig.3 Node layer

5. Applications

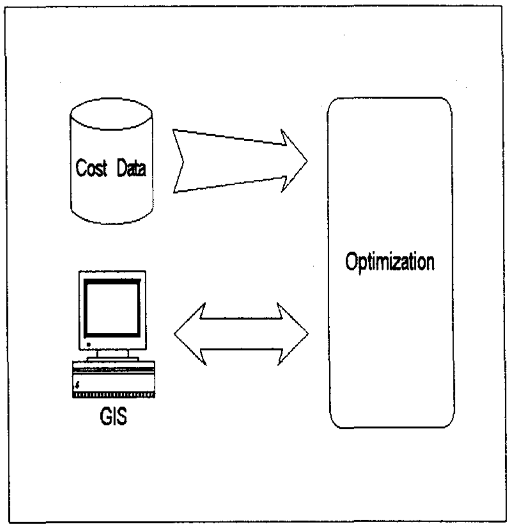

Fig.5 Data flow diagram

using GIS, study area is taken. Study area is northern part of Seoul. There metro water supply system is under construction. Which can afford to supply to the suburbs of Seoul at the rate of 200,000 ton per day. Intake station is located right after the Pal-Dang dam of Han river. Total length of pipeline is 55.9km.

Node data and pipeline data are given in table 2 and 3. In table 3, Diameter is result from traditional method.

Table 2. Node data

Node number	Demand (1000t/d)	Pipe level (m)
0	-200.0	6.50
1	0.0	72.15
2	9.0	25.15
3	10.0	41.13
4	0.0	80.00
5	0.0	80.00
6	60.0	96.50
7	14.0	57.50
8	0.0	77.50
9	3.0	91.50
10	104.0	47.50

Table 3. Pipeline data

Pipeline Number	Length (km)	Diameter (mm)
1	3.4	1350
2	11.5	1350
3	2.8	1350
4	0.8	1350
5	0.8	2000
6	4.3	1350
7	3.5	1000
8	5.3	1000
9	9.6	1000
10	6.3	1000

Using various typed data, source code of optimization package is prepared and optimal computation is operated. After computation, the diameter of each pipe and the location & optimal head of pump are determined. In this computation, the locations of pump are the starting points of pipeline of No.1, 4, 8, and optimal pumping head are 82.7m, 63.2m, 38.5m respectively. The diameter of each pipe is given in table 4, and the optimal cost is in table 5. Where diameter 1 and cost 1 are results from traditional method and diameter 2 and cost 2 are results from optimal computation.

6. Conclusions

The cost resulted from optimal computation is cheeper than the cost from traditional computation. The curtailment cost is 1 million dollors per year (10.7%) in annual cost aspect. (2 million dollors (4.3%) is curtailed in initial cost aspect.) The

Table 4. Optimal Diameter

Pipe Num.	Diameter 1 (mm)	Diameter 2 (mm)
1	1350	1350
2	1350	1350
3	1350	1350
4	1350	1350
5	2000	2000
6	1350	1350
7	1000	1000
8	1000	1000
9	1000	1000
10	1000	900(293m) 800(6007m)

Table 5. Optimal Cost

Cost Types	Cost 1 (million$/yr)	Cost 2 (million$/yr)
Pipeline	4.91	4.78
Pump Equipment	0.84	0.65
Pumping Station	0.35	0.38
Electric Charges	3.21	2.50
Total (Initial Cost)	9.31 (44.9)	8.31 (42.9)

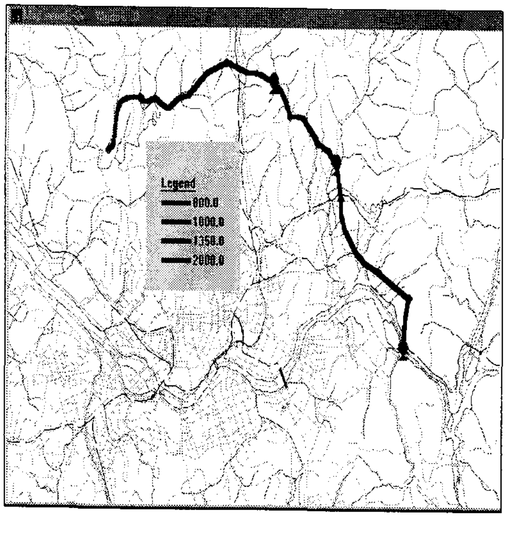

Fig.6 The results of optimal computation

reason the optimal computation must be operated in annual cost aspect is that the computation in annual cost aspect is more reasonable because it also considers pumping cost which occupies much portion of total cost(30%).

The model selects the optimal diameter not in the form of continuous number but in the form of commercial discrete diameter(pipe size) using the pipe lengths as decision variables instead of pipe diameters. The model not only determines the optimal pumping head for each pumping station but also finds the optimal location and number of pumping stations.

GIS is used to handle hydraulic and budgetary data automatically and to visualize the results for the optimal design of the system. The model has been applied to an existing water supply systems. The result show that the optimization model with the aid of GIS is helpful in the decision-making process for the design of more economical systems, and can be put into practice successfully.

References

Brooke, A., Kendrick, D., Meeraus, A. and Rosenthal, R. E.(1992), GAMS a User's guide, release 2.25, The Scientific Press

Diane Burke(1995), SPANS Explorer, Manual, TYDAC

Geem, Z. W.(1995), "A Study on the Optimal Design of Branched Pipeline Systems", M.S. thesis, Korea University

Jun, H. D., Kim, T. G., Kim, J. H., Yoon, Y. N.(1994), "Optimal Design of Dendritic Water Distribution Systems using Linear Programming", J. of Korean Association of Hydrological Sciences, Vol.27, No.3

Kim, J. H.(1992), "Optimal Rehabilitation/Replacement Model for Water Distribution System", Ph. D. Dissertation, The University of Texas at Austin

Mays, L. W. and Tung, Y. K.(1992), Hydrosystems Engineering and Management, McGraw-Hill, Inc.